Final Technical Report to the Office of Naval Research

Applied Oceanography Division

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Project: Mixed-Layer Parameterizations in Models of the Indian Ocean Circulation

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<u>Publications and Presentations from ONR Sponsored Research CY 1993:</u>

Luther, M. E., and J. C. Brock, 1993. Modelling the physical and biogeochemical patterns of the Indian Ocean for the Arabian Sea Process Study. US JGOFS News, Vol. 5, No. 1, pp. 4-5.

Bartolacci, D., M. E. Luther, and J. C. Brock, 1994. Historical observations of physical and biological parameters in the Arabian Sea. (Data atlas in preparation; anticipated publication in summer '94)

Valenti, M. G., and Luther, M. E., 1994. Interannual variability in the Somali Current, 1977-92. (in preparation).

Luther, M. E., C. J. Pursley and J. J. O'Brien, 1994. Variability in sea surface height in the equatorial Indian Ocean from Geosat and model data. *J. Geophys. Res.* (in preparation; more analysis is being performed on Geosat data and model results)

Luther, M. E., 1993. Dynamics of the Northern Indian Ocean and Model Investigations, in Report of the Seventh Session of the CCCO Indian Ocean Climate Studies Panel, edited by J. S. Godfrey, SCOR-IOC Report CCCO-IND-VII/3.

Luther, M. E., 1993. Modelling the Circulation of the Indian Ocean. Invited presentation at the University of Hawaii, Honolulu, Hawaii, March 30, 1993.

Luther, M. E., Z. Ji, and K. Chen, 1993. Near real-time modelling of the Indian Ocean wind-driven circulation. Invited presentation at The Oceanography Society Meeting, Seattle, WA, April 12-16, 1993.

Luther, M. E., 1993. Seasonal variability in the Indian Ocean and the WOCE Hydrographic Program. Presented at a meeting of the WOCE Indian Ocean Science Steering Committee, La Jolla, CA, August 2-5, 1993.

Luther, M. E., 1993. Ocean Modelling and Remote Sensing. Presented at the monthly meeting of the ACM/SIGGRAPH Tampa Bay Chapter, St. Petersburg, FL, September 8, 1993.

Luther, M. E., 1993. Modelling the variability of upwelling in the Arabian Sea. Presented at the Office of Naval Research, Arabian Sea Expedition Program Managers Meeting, October 25, 1993.

Luther, M. E., 1993. Indian Ocean circulation and the global climate system. Invited presentation in the Department of Marine Science, Eckerd College, October 27, 1993.

Research Abstract

Objectives:
The primary objective of this research is to implement and test improved mixed layer parameterizations in a layered numerical model of the Indian Ocean circulation. This will allow inclusion of thermodynamic forcing as well as wind stress forcing of the model circulation in order to understand the variability and complicated mixed-layer physics observed in the real Indian Ocean and to develop an optimum formulation for mixed layer physics in layered ocean models. Although these efforts are focused on the Indian Ocean, the formulation developed here can be extended to other areas of the world ocean.

Approach:
The ocean circulation model is that described in Luther and O'Brien (1985) as extended by Jensen (1991) and by J. Capella (personal communication). The present version of the model has 4 layers, with the horizontal pressure gradient assumed to vanish in the lowest layer (the reduced gravity approximation). The model domain covers the Indian Ocean basin from 30 degrees S to 26 degrees N and from 35 degrees E to 120 degrees E at a resolution of 1/12 degrees in latitude and longitude. Thermodynamic forcing through a simplified Kraus-Turner mixed layer parameterization as in McCreary et al. (1993) has been added to this version of the model. Entrainment and detrainment processes are included that allow water to move between layers. Detrainment simulates the subduction of surface-layer water into the deeper ocean. The entrainment and detrainment processes are dynamically similar to the vertical mixing of momentum and heat that is present in continuously stratified models. This improved model of the Indian Ocean is being evaluated against available observations and in comparison with a parallel model formulation being undertaken at NRL by Kindle and Gallacher.

Tasks completed:
A 20-year integration, driven by climatological monthly mean winds from the FSU analysis, has been used to "spin-up" the present version of the model (with wind stress forcing only). Using the end of this 20-year integration as an initial condition, a model integration has been completed using the monthly mean real-time winds processed at Florida State University for the period January 1977 through February 1994. This integration is updated through the 16th of the most recently completed month by the 5th working day of each month to provide a near-real-time "quick-look" estimate of conditions in the Indian Ocean. The results from this model integration are available to

the research community via anonymous ftp from kelvin.marine.usf.edu. These data are being used in planning the upcoming ONR Accelerated Research Initiative in the Arabian Sea and WOCE and JGOFS work in the Indian Ocean. From December 22, 1992, to March 9, 1993 there were 258 remote entries into the anonymous ftp directory from numerous US and international internet sites (we stopped keeping track of ftp entries after that period).

Interannual variability in the model circulation fields has been investigated for the period 1977-1992. A composite climatological seasonal cycle has been removed from the monthly mean fields of velocity, layer thickness, and sea surface elevation to create monthly anomaly fields. A 12-month running mean has been applied to the monthly anomaly fields to isolate the interannual variability. A complex empirical orthogonal function (CEOF) analysis is being performed on the monthly anomaly fields to identify the dominant modes of variability.

Implementation of the mixed-layer formulation of McCreary et al. (1993) into the circulation model code has been completed. Luther and a Ph.D. student, Zaihua Ji, are now testing this version of the circulation model with the assistance of J. P. McCreary. This model code has been given to John Kindle at NRL-SSC for evaluation. The accompanying figures show the model upper layer thickness, velocity, and mixed layer temperature for May 15 and August 15 after 12 years of spin-up using the climatological atmospheric forcing fields from Rao et al. (1989, *J. Geophys. Res.*, *94*, 10801-10815). After testing is completed, parallel runs of our model and the NRL model will be run, using identical forcing fields. Results of these model runs will be compared against each other and against observations.

Under separate funding from NSF and NASA, a biogeochemical model has been developed and is being coupled to the physical model. The improved mixed-layer formulation in the physical model provides information on mixed layer depth, nutrient entrainment and mixing intensity required by the biogeochemical model. The coupled physical-biogeochemical model will be applied to analysis and interpretation of the observations from the ONR-JGOFS Arabian Sea Process Study.

Results:

Significant interannual variability is found in the model fields. The dominant large-scale interannual variability occurs in the eastern tropical Indian Ocean and has similar characteristics to the Pacific ENSO phenomena in that it is instigated by eastward-propagating equatorial Kelvin waves. Associated with this mode of variability is a large-scale redistribution of mass in the upper layer of the ocean north and south of 10 degrees south latitude. The periods September 1979 to December 1981 and April 1983 to June 1985 appear as warm anomalies in the eastern tropical Indian Ocean, with the thermocline as much as 15 m deeper than usual. The periods February 1987 to August 1987 and January 1988 to December 1990 appear as cold anomalies with a shallower thermocline in the eastern tropical Indian Ocean. Gary Meyers and R. R. Rao (personal communication) see similar variability in XBT observations from the eastern Indian

Ocean.

Interannual variability in the western basin is of smaller spatial scale and is associated with year-to-year variations in the Somali Current-EACC system and the atmospheric Findlater Jet. Year to year variations in upwelling and primary production in the Arabian Sea during the period of 1979 through 1982 as presented in Brock and McClain (1991) can be understood in terms of changes in the strength of the wind stress curl field associated with the Findlater Jet. Changes in the wind stress curl field drive changes in Ekman pumping, leading to changes in the depth of the mixed-layer, the thermocline, and the nutricline. These changes are clearly seen in the variability in thermocline depth in the interannual model integration described above, leading to a better understanding of the relationship between Ekman pumping and mixed-layer evolution as modelled by Bauer et al. (1991).

Accomplishments:
The most important accomplishment to date from this work is the implementation of the model in near-real-time and the distribution of the results to the research community for use in planning future ONR, JGOFS, and WOCE observations in the Indian Ocean. By running the model with observed winds from the FSU analysis, we have provided a greater understanding of the variability in the Indian Ocean circulation.

Another significant accomplishment is the implementation of the mixed-layer parameterization in the Indian Ocean circulation model. The model code has been delivered to John Kindle at NRL-SSC. Continued development and testing of the model will be done in collaboration with Kindle and McCreary.

Influences:
Bauer, S., G. L. Hitchcock, and D. B. Olson, 1991: Influence of monsoonally-forced Ekman dynamics upon the surface layer depth and plankton biomass distribution in the Arabian Sea, *Deep Sea Res., 38*, 531-553.

Brock, J. C., and C. R. McClain, 1992: Interannual variability in phytoplankton blooms observed in the northwestern Arabian Sea during the southwest monsoon, *J. Geophys. Res., 97*, 733-750.

Jensen, T. G., 1991: Modeling the seasonal undercurrents in the Somali Current System, *J. Geophys. Res., 96*, 22,151-22,167.

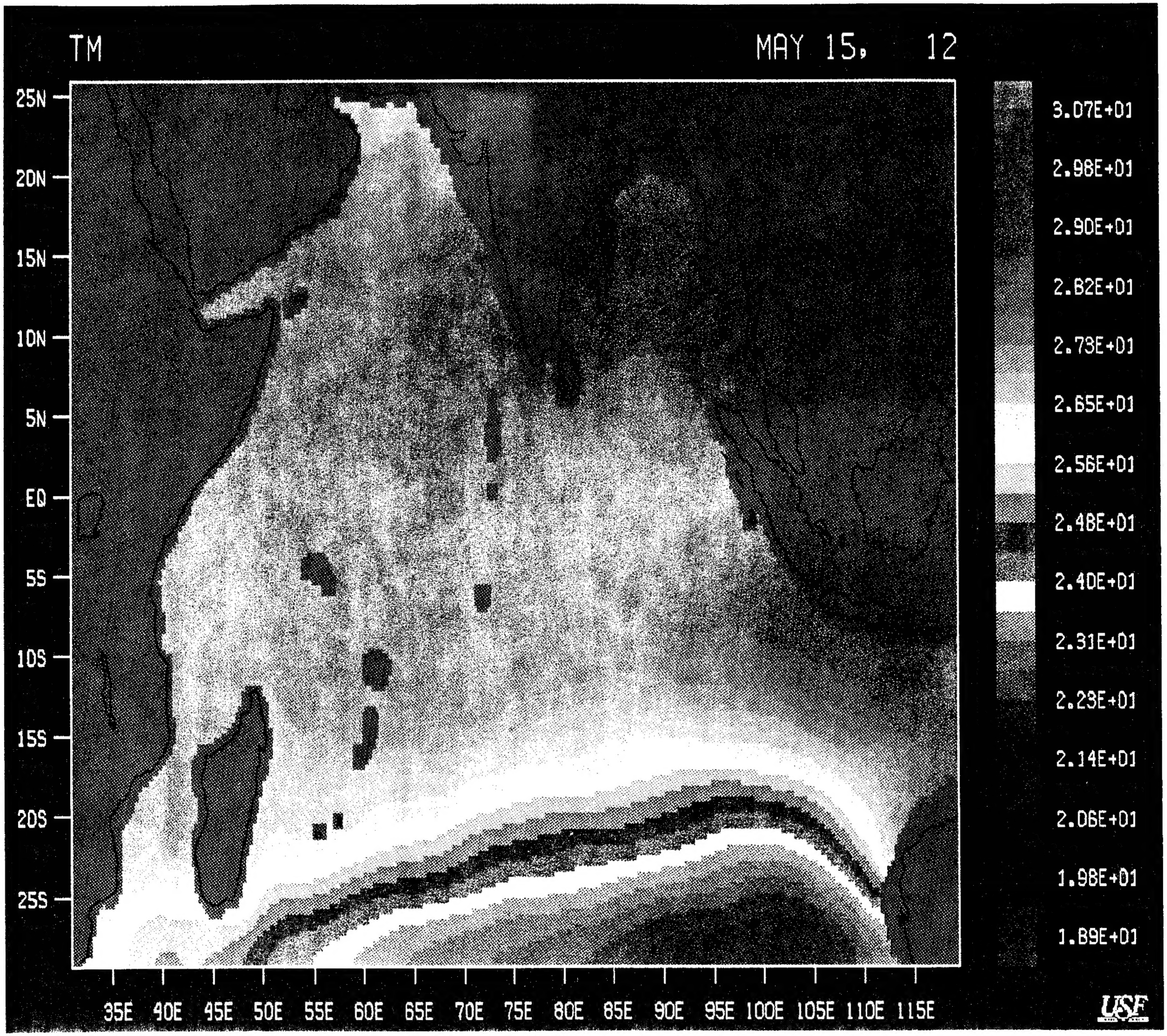
Legler, D. M., 1992: Analysis of air and sea physical properties and surface fluxes using a combination of in-situ and Seasat data, Mesoscale Air-Sea Interaction Group Technical Report, Florida State University, Tallahassee, 177pp.

McCreary, J. P., and P. J. Kundu, 1989: A numerical investigation of sea surface temperature in the Arabian Sea, *J. Geophys. Res., 94*, 16,097-16,114.

McCreary, J. P., P. J. Kundu, and R. L. Molinari, 1992: A numerical investigation of dynamics, thermodynamics, and mixed-layer processes in the Indian Ocean, *Progr. Oceanogr., 31,* 181-244.

Figure legend:

Mixed-layer temperature (TM), and upper layer (thermocline) depth and upper layer velocity for May 15 and August 15 after 12 years of spin-up forced by the climatological monthly mean atmospheric fields from Rao et al. (1989, *J. Geophys. Res., 94,* 10801-10815). Atmospheric fields consist of wind stress, wind speed, air temperature, and humidity. The model computes surface fluxes using these fields and its own mixed layer temperature from bulk aerodynamic fomulae. Color represents temperature or thermocline depth and arrows represent velocity (see scale bars and arrows). The model reproduces the warming of the Arabian Sea prior to the southwest monsoon onset and the cooling after the onset. The cold upwelling wedges observed in the two-gyre system of the Somali Current are simulated by the model.



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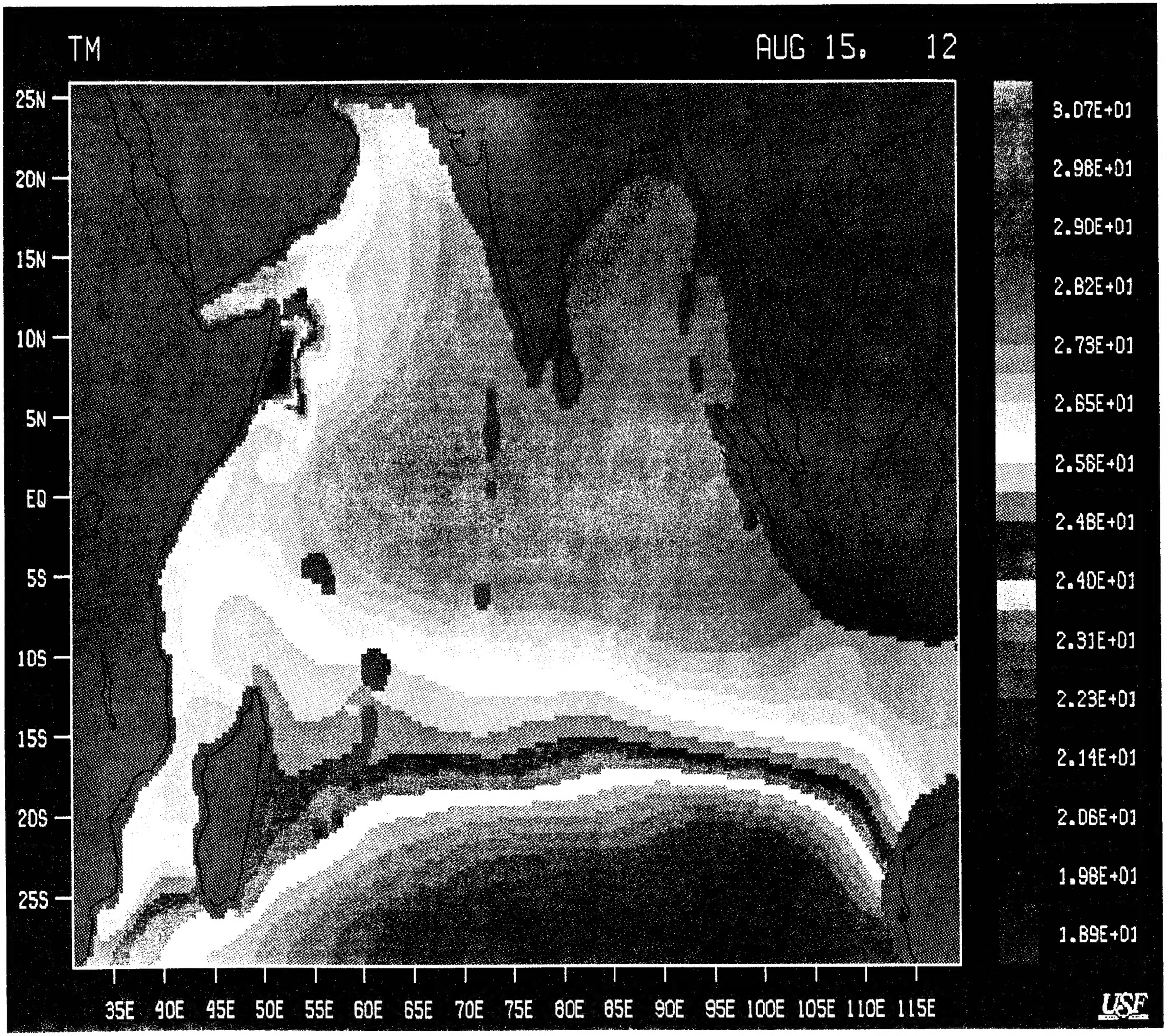
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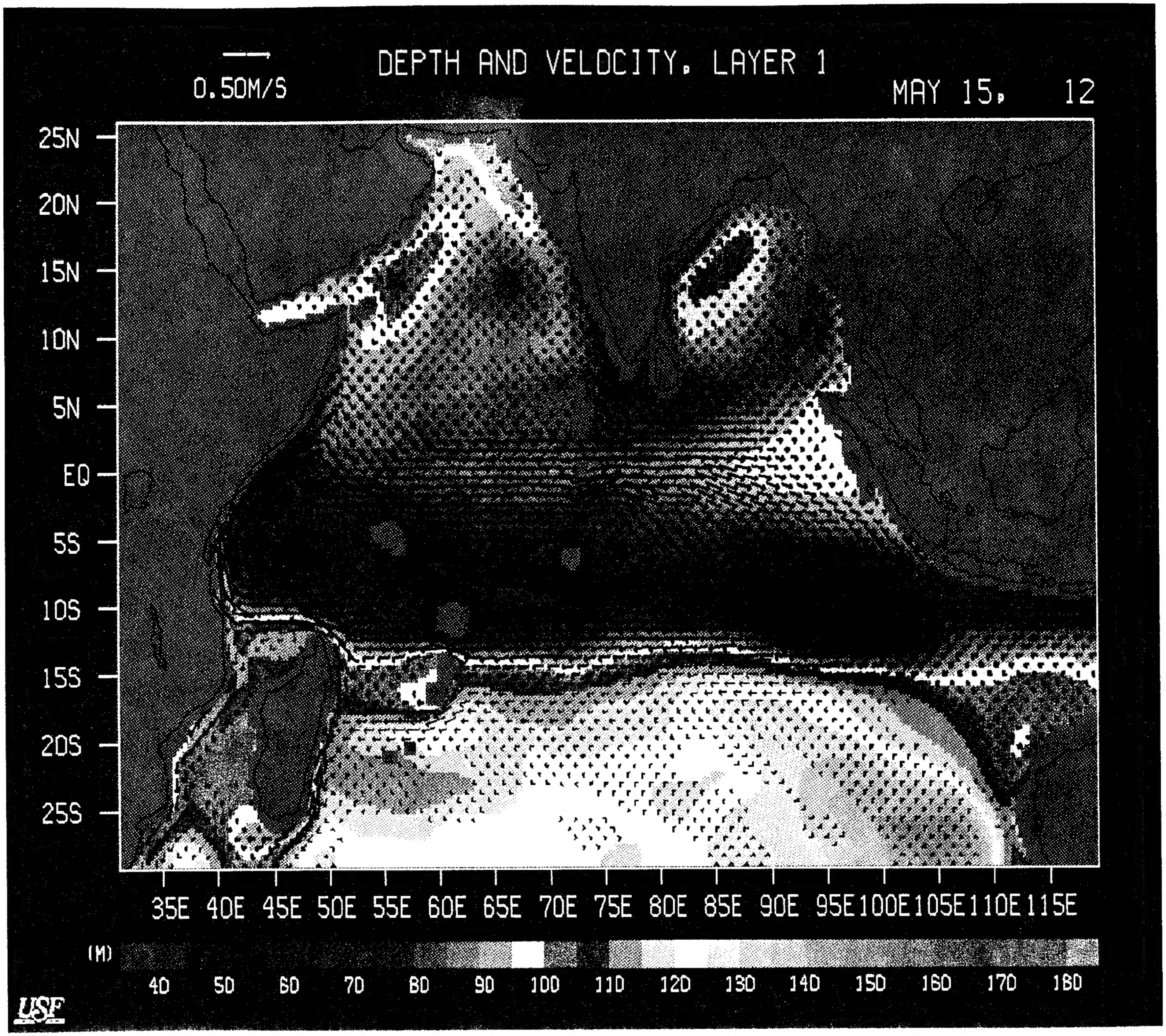
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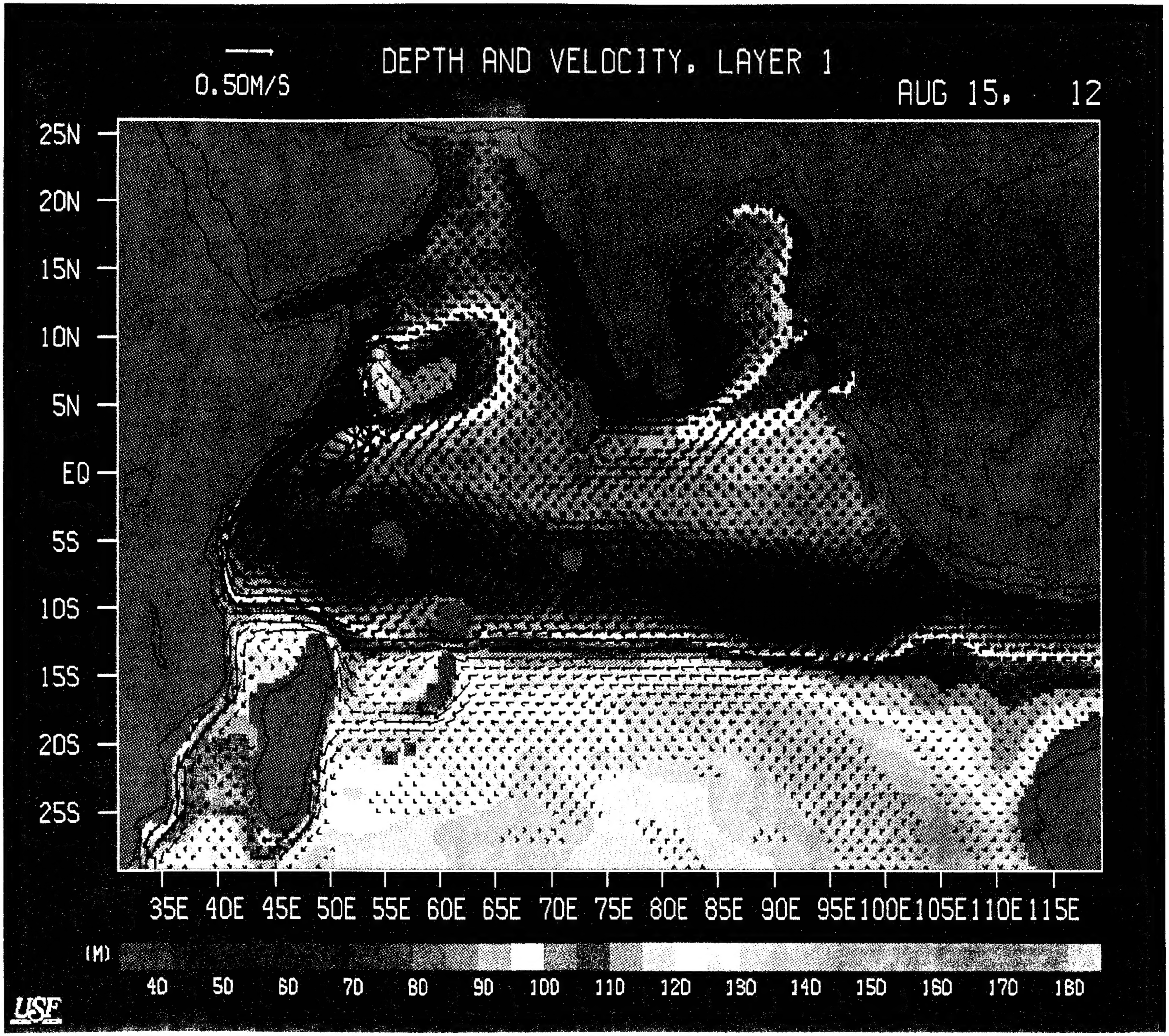
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